
THE
UNBALANCED ALTERNATING CURRENT
BRIDGE FOR MAGNETIC
ANALYSIS

By
ANATOLI C. SELETZKY

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THE UNBALANCED ALTERNATING CURRENT BRIDGE FOR MAGNETIC ANALYSIS

By W. B. KOUWENHOVEN¹ AND A. C. SELETZKY²

SYNOPSIS

An alternating current bridge has been developed which tests ferrous materials independently of their cross-sections. Two coils and two resistances, one of which is variable, constitute the four arms of the bridge. A standard specimen is placed in one coil and the unknown specimen in the other coil and the galvanometer deflection is reduced to zero by varying the resistance.

An alternating current galvanometer with a variable field phase displacement is used as a detector. By varying the phase of the galvanometer field the bridge may be balanced on any component of the exciting current flowing through the two coils. When the phase of the field has a displacement angle such that the bridge balances on either the loss or magnetizing component of the exciting current, specimens may be compared with a standard, provided they have the same length and cross-section; at a certain value of phase displacement of the galvanometer field, the bridge reading does not depend on the ratio of the cross-sections of the specimens being compared, but only on the character of the material, the lengths of the specimens being equal.

Specimens have been successfully tested, the cross-sections of which varied from one-quarter to twice that of the standard. Wide variations in voltage and frequency have no effect on the readings. The bridge has been studied analytically and the theory of operation is presented. The practical application of the bridge in this investigation was in the testing of pocket knife blades; it may be readily adapted, however, to the testing of many products made of ferrous materials.

INTRODUCTION

The segregation of ferrous materials by magnetic analysis using alternating current has been studied by deForest,³ Kouwenhoven,⁴ Spooner,⁵ Styri⁶ and Kouwenhoven and Tebo.⁷ An essential feature in their work was the use of an alternating current galvanometer, the

¹ Associate Professor of Electrical Engineering, Johns Hopkins University, Baltimore, Md.

² Graduate Student in Electrical Engineering, Johns Hopkins University, Baltimore, Md.

³ A. V. deForest, "A New Method of Magnetic Inspection," *Proceedings, Am. Soc. Testing Mats.*, Vol. 23, Part II, p. 611 (1923).

⁴ W. B. Kouwenhoven, "Magnetic Tests of A.S.T.M. Drills," *Proceedings, Am. Soc. Testing Mats.*, Vol. 24, Part II, p. 635 (1924).

⁵ Thomas Spooner, "The Magnetic Analysis of High-Speed Steel," *Proceedings, Am. Soc. Testing Mats.*, Vol. 26, Part II, p. 148 (1926).

⁶ Haakon Styri, "Testing of Ball Bearing Races by Electric and Magnetic Methods," *Proceedings, Am. Soc. Testing Mats.*, Vol. 26, Part II, p. 148 (1926).

⁷ W. B. Kouwenhoven and J. D. Tebo, "Incremental Permeability Method for Magnetic Analysis of High-Speed Steel," *Proceedings, Am. Soc. Testing Mats.*, Vol. 28, Part II, p. 356 (1928).

phase of whose field excitation could be varied. This renders the galvanometer sensitive to the component of the current in the moving coil, which is in the same phase as the galvanometer field. Generally, separation among specimens has been effected by measuring quantities, which are proportional either to the magnetization or the loss, or both, in the specimen.

Inasmuch as the magnetization or flux and the loss are different functions of the cross-section, the length being considered constant, the specimens being compared must be of equal size. This at once

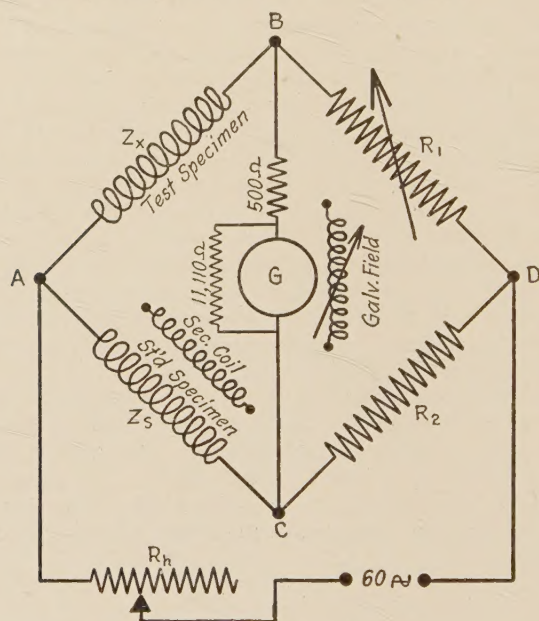


FIG. 1.—Diagram of Bridge Circuit.

limits the methods developed so far to materials or products which are of the same dimensions, a not altogether desirable restriction.

This paper describes a method of magnetic analysis which is independent of the cross-sections of the specimens within rather wide limits. It is based upon the comparison of a standard and an unknown specimen in an alternating current bridge in which the phase of the galvanometer field is adjusted to a component that is independent of the cross-sectional areas of the samples.

THE BRIDGE

The bridge used is shown in Fig. 1. Z_x and Z_s are two coils exactly alike of 400 turns each, 10 in. long, and having an ohmic resist-

ance of 1.22 ohms. These coils were built to accommodate steel specimens 10.2 in. long, 1.9 in. wide and from 0.061 to 0.135 in. in thickness. The fixed resistance R_2 had a value of 0.84 ohms, and R_1 was a variable slide wire resistance with 0.002888 ohms per scale division. The galvanometer used was a Leeds and Northrup pointer type alternating current galvanometer, with a sensitivity of one micro-ampere per mm. deflection, and a resistance of 250 ohms. The gal-

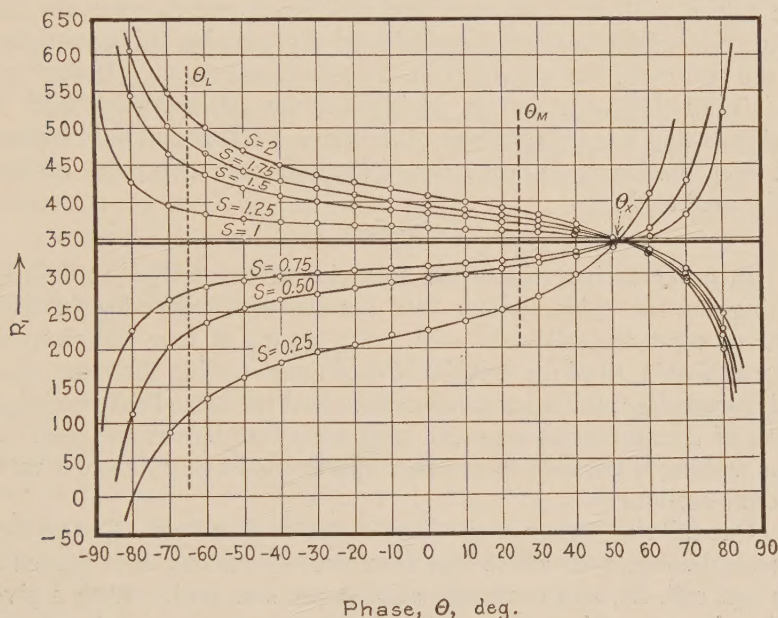


FIG. 2.—Variation of R_1 with Phase θ , of Galvanometer Field for Various Ratios, S , of Cross-Sections. Specimen A-1 in Standard Coil.

$$S = \frac{\text{Area of cross-section of test specimen}}{\text{Area of cross-section of standard specimen}}$$

vanometer coil was shunted with a resistance of 11,110 ohms for damping. An additional series resistance of 500 ohms was placed in the galvanometer circuit to limit the current through the instrument. The phase of the excitation of the galvanometer field was varied by means of a phase shifting transformer.

All of the measurements reported in this paper were made at 60 cycles. A number of tests were also made at other frequencies varying from 25 to 140 cycles. The resistance R_h was used to control the current through the bridge. The circuit was so arranged that the

currents I_x and I_s passing through the Z_x and Z_s coils, respectively, could be readily measured.

The coil, Z_s , containing the standard specimen was provided with a secondary winding for use in adjusting the phase relation of the galvanometer field. The phase of the galvanometer field at which the deflection produced by the voltage induced in this secondary coil was a maximum, was called θ_l and the position 90 deg. away θ_m . When the galvanometer was reconnected to the bridge the values of R_1 for balance at field position θ_l and θ_m were not only a function of the magnetic qualities of the samples being compared in the two coils, but also of their cross-sectional areas. However, it was found that at a certain position of the galvanometer field the bridge setting was independent of the cross-sections and only dependent upon the magnetic properties of the material; this point we have designated as θ_x .

THEORY

In order to investigate the behavior of the bridge at different settings of the galvanometer field for specimens differing in cross-section, sheet material was used. Six groups of four samples each were available, all of the samples of each group having the same chemical composition, the same cross-section, and the same heat treatment. Some of the specimens were cut lengthwise into halves and quarters, thus making it possible to compare specimens having different ratios of cross-section.

One full size specimen was kept in the standard coil, Z_s , and various combinations of whole and fractional specimens were placed in the test coil, Z_x , and compared against the standard. With a given ratio of cross-section, the phase of the galvanometer field, θ , was varied in increments of 10 deg., and the bridge balanced by adjusting R_1 . The results for one group of samples are shown in Fig. 2. The ratio of the area of cross-section of the test specimen to that of the standard is denoted by S . It will be noticed that when S is unity the bridge is perfectly balanced and the value of R_1 is constant for all displacements of the galvanometer field. This is what would be expected because the cross-sections and the magnetic qualities of the two specimens are alike and therefore the coil impedances are equal.

The important and peculiar features of all these curves is that they intersect at one point, θ_x , which shows quite definitely that the value of R_1 for balance, when the galvanometer field phase is at this point, is the same for all values of S , from $\frac{1}{4}$ to 2. The space within the coils did not permit the insertion of more than two whole specimens.

Similar sets of curves were obtained with the other groups of

specimens. The values of θ_x , however, differed as did also R_1 ; by virtue of these differences it was possible to obtain magnetic separation independent of cross-section over the range studied.

All of the curves in Fig. 2 may be expressed as a function of the tangent of the field displacement angle θ by the following equation:

$$R_1 = R_0 + A \tan \theta$$

In this equation, R_1 is the value of R_0 at the flex point of the curve and A is a constant which is a function of the ratio of cross-sections. In Fig. 2 the variation of R_1 with θ is given for 180 deg. only. When carried through the full 360 deg. the curves repeat.

The horizontal line for $S = 1$ is simply the limiting condition at which A is zero. This denotes a perfectly balanced bridge and for all other values of S the bridge is not truly balanced, since the impedances of the two coils are then unequal and the only variable is R_1 . The galvanometer deflection is reduced to zero by the variation of R_1 and this partial balance is only true for a particular position of galvanometer field displacement.¹

MANIPULATION

In using the bridge for the actual separation of specimens the method of procedure was as follows: Two specimens alike in quality and area were put in the bridge, one in each coil, and the current adjusted to the value at which the run was to be made. The bridge was balanced by means of R_1 . Under these conditions the bridge balance is perfect and independent of the position of the galvanometer field. This condition is represented by the horizontal line for $S = 1$, as shown in Fig. 2. The full size specimen was now withdrawn from the test coil and another specimen of the same magnetic properties but of different cross-section was inserted in its place. This resulted in a galvanometer deflection which was reduced to zero by varying the phase of the galvanometer field without disturbing the resistance R_1 in any way. This phase angle of the galvanometer field at this point we have called θ_x .

With the galvanometer field in this position the bridge was ready for operation. Various specimens were now introduced into the test coil and if the R_1 reading necessary for balance did not change the specimens had the same magnetic properties as the standard. On the other hand a change in R_1 for balances denoted a variation in the magnetic properties of the specimens. Under these conditions the R_1 readings were a function of the quality of the material and not its

¹ See Appendix, p. 12, for further discussion of theory.

cross-section. The current through the test coil was held constant during a run by varying the voltage across the bridge. The ammeter was not in circuit at the time of obtaining a balance.

RESULTS

A number of tests were made on samples of different kinds and cross-sections, and as a practical check of the value of the method

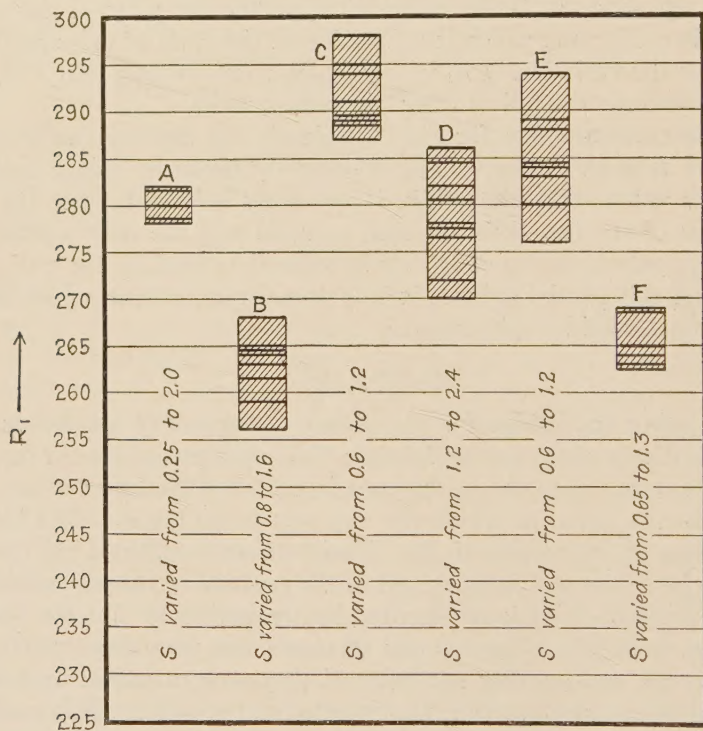


FIG. 3.—Separation of Specimens of Varying Chemical Compositions. Specimen A-1 used as standard.

pocket knife blades of various areas were used. Two typical sets of results are reported, one on annealed strip material varying slightly in chemical composition, and the other on knife blades of varying heat treatments.

Tests of Annealed Strip Material:

The six groups of specimens already mentioned were of annealed strip stock and were designated as A to F, inclusive. Their chemical composition is given in Table I, and all meet the same purchasing specifications. The hysteresis loops of these specimens showed only

slight differences, none of which were sufficient to afford positive identification of any particular group.

As stated above, some of these specimens had been cut into narrow strips. They were all tested in the alternating current bridge with the galvanometer field at the θ_x position. Tests were made at different values of current and also with constant voltage across the Z_x coil. A typical set of results at a constant exciting current of 0.5 ampere are given in Fig. 3. One full size specimen, A-1 from group A, was used as the standard, and all of the other specimens of various cross-sectional areas were compared against it. In Fig. 3 the values of R_1 are plotted as ordinates and there are no abscissas. Horizontal lines one division in length are drawn to denote more prominently the value of R_1 pertaining to a particular specimen. The lines belong-

TABLE I.—CHEMICAL COMPOSITION OF STRIP MATERIAL.

	Carbon, per cent	Manganese, per cent	Phosphorus, per cent	Sulfur, per cent	Silicon, per cent	Chromium, per cent
Group A.....	1.04	0.33	below 0.025	below 0.025	0.10 to 0.25	0.04
Group B.....	1.02	0.30	below 0.025	below 0.025	0.10 to 0.25	0.07
Group C.....	1.02	0.22	below 0.025	below 0.025	0.10 to 0.25	none
Group D.....	1.03	0.37	below 0.025	below 0.025	0.10 to 0.25	0.07
Group E.....	1.00	0.22	below 0.025	below 0.025	0.10 to 0.25	none
Group F.....	1.02	0.31	below 0.025	below 0.025	0.10 to 0.25	0.03

ing to any one group are blocked together as shown. These blocks represent the range of values for R_1 obtained for any particular group of specimens which varied widely in area as compared to the standard specimen. The range in area of the specimens in each group is noted in Fig. 3.

It is evident from Fig. 3 that in spite of wide differences in cross-section and only slight variations in chemical composition, the method segregated successfully those specimens belonging to group A from those of groups B, C and F. Some specimens belonging to groups D and E, however, are not separated from those of group A.

The difficulty confronted in the further separation of these groups, varying so little from one another, is that inherent in all methods of magnetic analysis. If the quantity, which is employed as the criterion for separation, is affected to the same or different degrees by a number of variables present, then it is possible for different combinations of these variables to give the same value for the characteristic being measured. In this particular case the variables are carbon, manganese and chromium and when two particular groups of specimens overlapped, it simply meant that the chemical constituents present affected the magnetic characteristics of the two materials in such a

manner that there was no distinction between their R_1 readings. It should be kept in mind that the segregation obtained was made by means of a single reading R_1 , at a given setting of the galvanometer field on four of six groups of steel, all of which met the same purchase specifications.

Tests of Knife Blades:

A number of groups of pocket knife blades in various stages of manufacture were furnished by the Winchester Repeating Arms Co., as a practical test of the method. These blades had all been cut from the same lot of stock and were in various stages of manufacture. The overall length of the blades was approximately 3.3 in., the depth

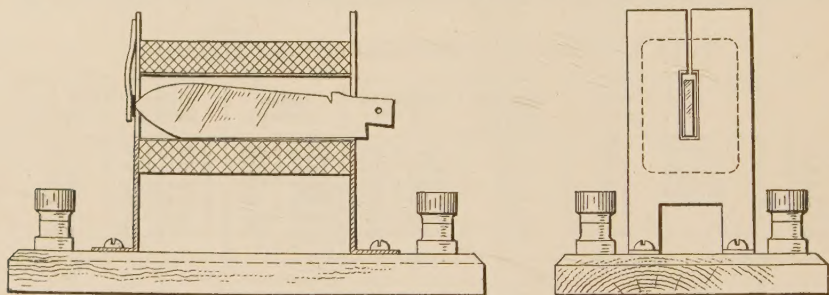


FIG. 4.—Coil for Testing Knife Blades.

0.7 in., and the thickness before grinding 0.1 in. There were two lots of blades designated as A and B, respectively, and a standard group Nos. 70 to 75, the individual blades of each lot being numbered consecutively. Lot B and the standard group had been quenched at a temperature 50° F. higher than lot A. All of the blades, however, had been drawn at the same temperature. Blades No. 71 to 75 and group B-1 blades were heat-treated unground blades. Groups A-2 and B-2 had been rough ground and groups A-3 and B-3 were finished blades. The grinding process reduces the cross-section of the blades to slightly less than half that of the original section.

Two new coils were wound identically alike to accommodate these blades; their construction is shown in Fig. 4. The winding consists of 720 turns of No. 22 D.C.C. copper wire wound on a rectangular brass shell, split along its length to avoid eddy currents. The knife blade was inserted into the coil until the point touched the stop at the rear end, in which position the tang of the blade projected out of the coil as shown. All of the blades were tested in this position. To avoid the possibility of having the blade and the brass shell

form a short-circuited secondary winding of a single turn, the inside of the tube was lined with treated tape. A secondary winding was provided on the coil which contained the standard specimen.

The inductance and effective resistance of the coils were measured at 60 cycles. The insertion of an unground knife blade in the coil increased the inductance from 3.2 to 20.1 millihenrys, the resistance from 3.7 to 4.7 ohms, and the impedance from 3.9 to 8.9 ohms.

Several of the blades were broken off lengthwise to provide specimens of reduced cross-section with which to locate θ_x . The

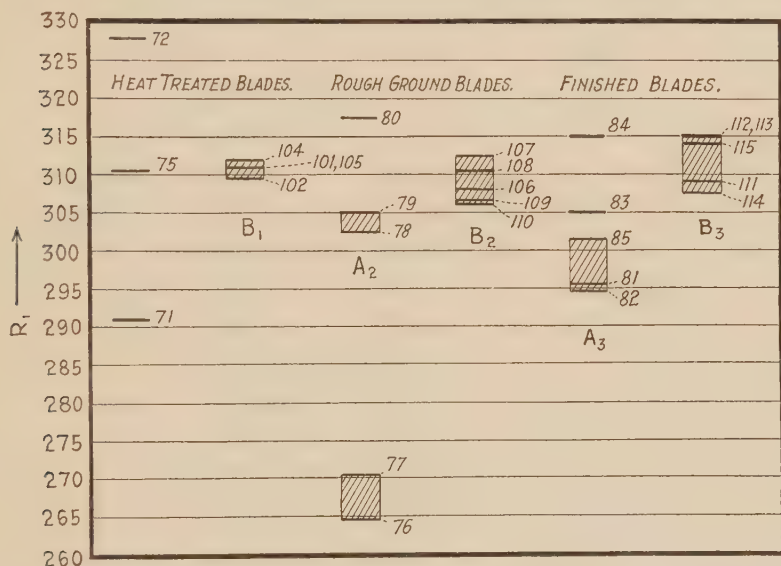


FIG. 5.—Results of Tests on Pocket Knife Blades.

Blade No. 74 used as standard.

same bridge was employed as in the preceding work, the new coils merely replacing the larger ones used for the sheet steel.

We hardened some blades and softened others, in order to ascertain the significance of changes in the R_1 readings. Blades 71, 76 and 77 were hardened by heating them to a temperature of 1700°F . and quenching in water; blades 72 and 80 had their temper drawn by heating to a red color and then allowing them to cool slowly in air. Blades 73, 74 and 75 were normal, blade 74 was used in the standard coil, and blade 73 was broken to reduce its cross-section.

In Fig. 5 are presented typical results, the values being plotted in the same manner as in Fig. 3. The numbers to the right of the lines denoting the R_1 readings are the code numbers of the blades. The

Brinell hardness tests were made with a Baby Brinell Tester, using a $\frac{3}{32}$ -in. diameter ball under a 170 kg. load.

The effect of a softened blade is to increase the value of R_1 in comparison to the normal reading, and that of a hardened blade to decrease its value. This is clearly shown by the location of the softened blades, Nos. 72 and 80, and the hardened blades, Nos. 71, 76 and 77.

The blades are listed in Table II in ascending order of their R_1 readings together with the corresponding Brinell hardness numbers. In general, considering the localized character of the Brinell hardness numbers there is agreement between them and the magnetic results.

TABLE II.—TESTS OF KNIFE BLADES.

Lot A				Lot B			
Blade	R_1 Reading	Brinell Hardness Numbers		Blade	R_1 Reading	Brinell Hardness Numbers	
		Point	Body			Point	Body
No. 71.....	291.0	...	657+	No. 102.....	309.5	426	592
No. 75.....	310.5	544	572	No. 101.....	311.0	380	572
No. 72.....	328.0	...	254	No. 105.....	311.0	396	592
				No. 104.....	312.0	396-408	408
No. 76.....	284.5	...	...	No. 110.....	306		600
No. 77.....	270.5	...	657	No. 109.....	306.5	380-408	592
No. 78.....	302.5	...	592	No. 106.....	308.0	600	623
No. 79.....	305.0	592	623	No. 108.....	310.5	426	600
No. 80.....	317.5	...	225	No. 107.....	312.5	592	600
No. 82.....	294.5	592	623	No. 114.....	307.5	592	600
No. 81.....	295.5	592	600	No. 111.....	309.0	592	623
No. 85.....	301.5	572-592	...	No. 115.....	314.0	592	572
No. 83.....	305.0	503-519	623	No. 112.....	315.0	572	592
No. 84.....	315.0	355	426	No. 113.....	315.0	396	355-365

The relative degrees of hardness in blades No. 71 to 75 and group A-2 is at once apparent.

The blades in group B-1 are very close together magnetically and the Brinell hardness numbers are also quite close, with the exception of blade No. 104, whose Brinell number is 408. The R_1 reading indicates that this blade is the softest of the group, but from the Brinell hardness value it should be higher and further displaced from the others. The magnetic and Brinell hardness results check throughout for the blades in group B-2.

The finished blades in group A-3 were all supposed to be standard. The magnetic test, however, showed that blades Nos. 84 and 83 were soft, particularly No. 84. The Brinell hardness test revealed that blade No. 84 was considerably softer than normal and that in the case of No. 83, although its body was of normal hardness, its point was soft. In the group of finished blades B-3, the R_1 values for blades

Nos. 112 and 113 were the same, although the Brinell hardness test indicates that No. 113 is the softer of the two.

With the exception of two blades, Nos. 104 and 113, there is a good correlation between the magnetic results and the Brinell hardness numbers. The R_1 value is quite distinct and is affected by the entire body of the blade in the test coil, whereas the Brinell hardness number is a function only of the hardness of the material under the ball. It is also interesting to note that the magnetic test results bring out the difference in the quenching temperatures of the two lots of blades, although their Brinell hardness numbers are the same.

This test on knife blades also shows clearly the independence of the bridge results of differences in area. The blades in the standard and B groups had all received the same heat treatment, but the standard blade and those in group B-1 were of unground cross-section. The grinding, sharpening and polishing operations are supposed to be carried out in such a manner as to preserve the temper of the blades. The data of Fig. 5 shows that group B-2, which had been ground, and B-3, which had in addition been sharpened and polished, retain their physical properties.

In the tests that have been reported in this paper, the current in the test coil was maintained constant at 0.5 ampere. Other values of current were used and measurements were also carried out maintaining the voltage across the test coil constant. The relative separation attained under these conditions was the same as that with the constant current of 0.5 ampere. Furthermore, it was found that when the bridge was once adjusted for a normal test specimen, the balance was not upset by the small change in current through the test coil caused by the variation in R_1 , necessary to balance for a non-standard specimen. This means that measurements could be made on various specimens without readjusting the current for each new balance point, that is, the testing could be performed with a constant voltage across the bridge.

With the bridge balanced for two normal blades, the frequency of the supply was varied from 49 to 83 cycles without disturbing the balance. Hence it may be said that when operating the bridge at 60 cycles the ordinary frequency fluctuations do not affect the separation.

CONCLUSIONS

The following conclusions may be drawn from this investigation:

1. An "unbalanced" alternating current bridge using an alternating current galvanometer has been developed for magnetic testing. In this bridge there is a certain position of the phase of the galvano-

meter field at which the bridge balance depends only upon the relative magnetic qualities of the specimens compared, and not upon the area of their cross-sections, within the range studied.

2. Data have been presented showing that segregation has been attained between standard and non-standard specimens, with the cross-section of the test specimen varying from one-quarter to twice that of the standard specimen, the lengths remaining constant.

The investigation is being continued and it is hoped that the

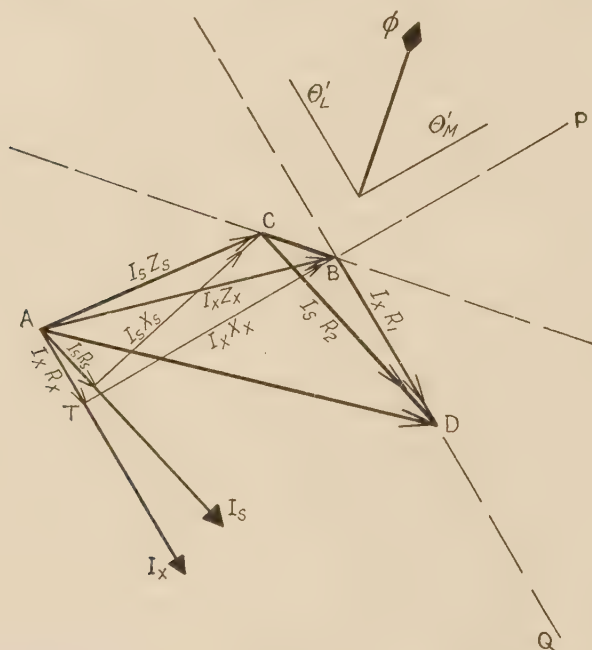


FIG. 6.—Vector Diagram of Bridge Circuit.

complete theory will be developed and additional data secured for presentation in a later paper.

Acknowledgment.—The authors wish to express their sincere appreciation to the Winchester Repeating Arms Co. for furnishing the test specimens, making the chemical analyses and Brinell hardness measurements and for their whole-hearted cooperation throughout the entire course of this work.

APPENDIX

Further Discussion of Theory:

The behavior of the bridge may be readily understood from its vector diagram, Fig. 6. Here I_s and I_x represent the currents through the standard

and test coils respectively. The current I_x was maintained constant at 0.5 ampere by varying the applied voltage. Hence for a given ratio of sections the impedance drop AB across the test coil was fixed. The vector AC equals the impedance drop across the standard coil. If the ratio of the cross-sections of the two specimens is unity and their magnetic qualities are alike, the points B and C will coincide, I_x and I_s will be in phase, the respective resistance drops $I_x R_1$ and $I_s R_2$ will be equal and in phase. Under these conditions the bridge will be perfectly balanced for all positions of the galvanometer field. If, however, either the cross-sections are unequal or the magnetic characteristics unlike, the points B and C will not coincide and there will be an unbalanced vector BC across the galvanometer terminals.

The deflection of an alternating current galvanometer is proportional to that component of the current flowing through its moving element which is in phase with the field flux; that is, in vector representation the deflection is proportional to the projection of the current vector on the field flux vector. Therefore, if the galvanometer field, represented by Φ , is in the position as shown in the diagram, it is necessary to vary R_1 until the vector CB assumes a position at right angles to Φ .

When the unbalanced vector CB has been brought to a position at right angles to the field, the galvanometer deflection is reduced to zero, but there will remain a small quadrature component of current flowing through the moving element. This galvanometer current is less than 0.2 per cent of the current flowing through the specimen coils, because of the high resistance of the galvanometer circuit as compared to that of the bridge. This quadrature current may therefore be neglected and the $I_s R_2$ and $I_x R_1$ voltage drops may be considered as in phase with their respective currents.

As the current I_x is maintained constant, the variation of R_1 necessary for balance modifies the applied voltage across the bridge, thereby also varying the current I_s . However, since $I_x R_1$ always remains in phase in the $I_x R_x$ the terminal point D will move along the line BQ . When R_1 has been adjusted to such a value that CB is perpendicular to Φ , the applied voltage AD will be determined by the intersection, D , of $I_x R_2$ and $I_x R_1$.

The explanation for the asymptosy of the curves in Fig. 2 may be readily seen in the vector diagram. The lines marked θ'_L and θ'_M represent Φ when it is in phase with the loss and magnetizing components $I_x R_x$ and $I_x X_x$, respectively. Now as Φ approaches the position θ'_L the unbalanced vector CB , which is kept in quadrature with Φ by adjustment of R_1 , approaches parallelism with the line TBP ; this means that $I_s R_2$ becomes more nearly parallel with $I_x R_1$ and the intersection of their two resistance drops, D , moves further out along BQ . When Φ lies in the position marked θ'_L then C must fall on the line TBP on one or the other side of B ; C cannot coincide with B because the impedances Z_s and Z_x are unequal. However, in this case the resistance drops CD and BD would be parallel and therefore under this condition it would be impossible to have the intersection D . This means that with Φ along θ'_L the galvanometer deflection cannot be reduced to zero. This also explains why as Φ approaches θ'_L the values of R_1 for balance increase so rapidly and tend to become infinite at θ'_L .

The lines θ'_L and θ'_M on the vector diagram are the theoretical positions. The points in Fig. 2 marked θ_L and θ_M are those obtained experimentally by means of the secondary winding and do not coincide with the theoretical posi-

tions by reason of the fact that the applied voltage on the test coil is not exactly 180 deg. out of phase with the induced voltage due to the power factor of the circuit. The unbalanced vector, BC , may be expressed as:

$$\dot{E}_{BC} = \dot{I}_x R_1 - \dot{I}_s R_2$$

Expanding this and substituting the value of I_s in terms of I_x gives:

$$\dot{E}_{BC} = \frac{\dot{I}_x R_1 (R_2 + R_s + jX_s) - \dot{I}_x R_2 (R_1 + R_x + jX_x)}{R_2 + R_s + jX_s}$$

For zero galvanometer deflection with unequal specimens the vector BC must be perpendicular to the phase of the galvanometer field Φ . The value of R_1 required to satisfy this condition was determined from the above relation, and the phase, θ , of the field and is given by the equation:

$$R_1 = \frac{R_2(R_2 R_x + R_s R_x + X_s X_x) - R_2(R_s X_x + R_2 X_x - R_x R_s) \tan \theta}{Z_s^2 - R_2^2 - R_s R_2 - R_2 X_s \tan \theta}$$

where R_x , R_s , X_x and X_s are the effective resistances and reactances of the test and standard coils, respectively, when the specimens are within the coils.

Attempts to express R_1 as a function of the cross-sections of the standard and unknown specimens have thus far been unsuccessful.

VITA

Anatoli Constantinovitch Seletzky, son of the Rev. Constantine Vasilyevitch and Antonina Franzevna Seletzky, was born in Volynia, Russia, May 29, 1905.

He received his primary and secondary education in the Friends School of Baltimore, graduating in June, 1923. In October of the same year he matriculated at the Johns Hopkins University as a student in Electrical Engineering and graduated with the degree of Bachelor of Engineering in June, 1927. He returned to the Johns Hopkins University in October, 1927, as a graduate student in Electrical Engineering, where he studied under Professor J. B. Whitehead and Associate Professor W. B. Kouwenhoven. Throughout the entire seven years of his residence at Hopkins he was a holder of a Foreign Scholarship.

During the summers of 1926, 1927 and 1928 he was employed by the Westinghouse Electric and Manufacturing Company and completed their "Graduate Students' Course." During the summer of 1929 he was engaged in the research laboratory of the Brooklyn Edison Company, Inc., in Brooklyn, New York.

